LCA Methodology

"Less is Better" and "Only Above Threshold": Two Incompatible Paradigms for Human Toxicity in Life Cycle Assessment?

José Potting, Michael Hauschild, Henrik Wenzel

Process and Production Engineering, Department of Manufacturing Engineering, Technical University of Denmark, Building 424, DK-2800 Lyngby, Denmark

Corresponding author: José Potting; e-mail: jp@ipt.dtu.dk

Abstract

The absence of spatial and temporal information in the data from a typical Life Cycle Inventory puts constraints on the possibilities of subsequent Life Cycle Impact Assessment to predict actual impact. Usual methods for Life Cycle Impact Assessment (often referred to as "less is better" methods) make only limited use of spatial and temporal information, because they predict concentration increases rather than full concentrations. As a consequence it does not seem possible to evaluate whether a threshold value is surpassed. The resulting poor accordance between the predicted impact and the expected occurrence of actual impact is a major problem. This problem is particularly relevant for human toxicity assessment, since the probability of surpassing thresholds here traditionally is the main point of attention. A considerable group of practitioners suggests to follow an "only above threshold" principle by introduction of assessment tools from risk assessment and environmental impact assessment in LCA. Intensive debate is going on about possibilities and limitations of "less is better" and "only above threshold". The debate is obscured by two underlying discussions (about no-effect-levels and about data-availability) that are partly, but not fully intertwined. Both principles tend to be given fixed positions in these discussions, and are therefore often put forward as fundamentally different and incompatible with each other. This article entwines the discussions, shows parallels between both principles, and uses these parallels to present a new method for Life Cycle Impact Assessment of human toxicity from air emissions that – with limited data requirement from Life Cycle Inventory – can take as well threshold evaluation and spatial source-differentiation into account.

Keywords: Human toxicity, methodology; methodology, paradigms, less is better, only above threshold; pollution prevention, emissions, methodology

1 Introduction

The international agreement about main lines of Life Cycle Assessment (LCA) is on a general level, since the method is not yet fully developed (Consoli et al. 1993, ISO/TC-207/SC5). In particular the impact assessment phase has not crystallized out. A major problem is the poor accordance between the impact predicted by a typical Life Cycle Impact Assessment (LCIA) and the expected occurrence of actual impact, in particular for human toxicity. The absence of spatial and temporal information in the data from a typical Life Cycle Inventory (LCI) puts constraints on the possibilities of subsequent LCIA to predict actual impact. Usual LCIA methods calculate similar impact for all emissions of the same size and substance, independently of the circumstances under which the emissions take place. In particular, for human toxicity assessment this may result in obviously wrong conclusions as illustrated in Box 1.

There is ongoing discussion about the possibilities and limitations of the impact assessment phase in LCA to predict actual impact. Two main positions can be distinguished: methods following the "less is better" principle (first used and still typical), and methods following the "only above threshold" principle (later introduced). The two principles and related methods are often put forward as fundamentally different and incompatible with each other (Barnthouse et al., 1997; Udo de Haes, 1996; White et al., 1995). We only partly agree and see, quite the reverse, clear analogies. However, these analogies are obscured by two interwoven discussions in which both principles unnecessarily seem to take fixed and opposite positions: The discussions about threshold evaluation in LCIA, and the availability of data from LCI to support such evaluation.

In this article, we will demonstrate that the only fundamental difference between "less is better" and "only above threshold" methods is the way they deal with exposure situations below and above threshold values. Neither the availability of spatial and temporal data, nor the level of sophistication of analytical tools for impact assessment are fixed in relation to the method being "less is better" or "only above threshold". This is illustrated with the assessment of human toxicity from air emissions. Next, we combine analytical tools of both prin-

Int. J. LCA 4 (1) 16 – 24 (1999)

Box 1: Three examples where Life Cycle Impact Assessment of human toxicity obviously results in wrong conclusions if circumstances in which emissions take place are disregarded

First example: single source exposures below/above threshold

In the Life-Cycle of linoleum, emission of toluene takes place during manufacture as well as in the use stage from the adhesive for laying the linoleum. Considerable dilution of the outdoor emission from linoleum manufacture results in ambient concentrations that remain far below the no-adverse-effect-level for toluene. The indoor toluene emission from the adhesive, however, gives cause to concentrations and exposures above the no-adverse-effect-level during at least 10-15 days (GUSTAFSSON, 1992; POTTING and BLOK, 1994).

Second example: multiple source exposures below/above threshold

Exhaust gases from transport vehicles contain a mixture of substances. Concentrations and exposures above no-effect-level are not expected to occur easily from roads outside built-up areas. The traffic density and moderate circulation on arterial roads in built-up areas easily brings about concentrations above no-effect-level by accumulation of exhaust gasses from all vehicles passing. In addition, also population density in the vicinity of these roads will be higher. According to KILDE et al. (1995), kilometres from lorry traffic in Denmark go for about 20-40% through built-up areas, 15-40% on motorways and 40% on secondary roads.

Third example: single source exposures below threshold

The emissions from electricity production for the public grid will be released from a stack that is often higher than 100 metres, whereas the stack height for an average production process is expected to be around 25 metres. Though both emissions will probably not give cause to concentrations above threshold, dilution from a high stack is considerably larger than that of a low stack. The actual exposure increase by the emission from electricity production is therefore expected to be much smaller than that from an average production process (though in the former case the surface of the area with an increased concentration, and therewith the number of exposed people may be larger).

ciples to arrive at a framework for human toxicity assessment from air emissions in LCA. A later article will report on the elaboration of this framework into factual factors to assess human toxicity from air emissions in LCA.

Nowadays, addressing human toxicity is much less related to acute exposures and effects than was the case a few decades ago, but has shifted to long-term exposure to dilute mixtures of compounds. As is discussed in Section 3, the classical idea of a no-effect-level has become troublesome in this situation. Addressing actual exposure and subsequent threshold evaluation gives rise to a need for data additional to what is usual in present impact assessments. Section 4 shows that such a need for data cannot always be fulfilled, although limited additional data often is available. Sometimes even an abundance of additional data can be obtained from Life Cycle Inventory. An increasing level of available data allows for analytical tools that can predict exposure and impact with increasing accuracy. Section 5 shows that there are already existing LCIA methods in use with different levels of data demand and accuracy of prediction (with regard to both "less is better" and "only above threshold" methods). However, yet not present is a "less is better" method that can distinguish in a simple way between below and above threshold situations. Section 6 gives a general outline how such a method can be drawn by combining elements taken from both "less is better" and "only above threshold" methods. A practical work program is set in Section 7.

2 "Less Is Better" and "Only Above Threshold"

The data from a typical LCI do not contain time and space specification. The absence of this information puts constraints on the possibilities of LCA to predict actual impact. Some practitioners have suggested to omit the impact assessment phase from LCA. This opinion is not shared by the mainstream of LCA practitioners, and it also contradicts with the requirements for an LCA as formulated by acknowledged authoritative bodies such as SETAC (CONSOLI et al., 1993; FAVA et al., 1993) and ISO (ISO/TC207/SC5). However, both SETAC and ISO recognize explicitly that LCA, and in particular the impact assessment phase, is still in an early stage of development.

Usual LCIA methods do not require, or only make limited use of spatial and temporal information by following a "less is better" principle. In present "less is better" methods, all emissions of a given substance are summed up throughout the life cycle. In a subsequent step, the cumulated emission of this substance is aggregated by equivalency assessment with the cumulated emissions from other substances contributing to the same impact category. All emissions are considered to be relevant on the basis of their intrinsic harmful properties. The underlying assumption is that all emissions give rise to concentration or deposition increases at sites that all have a similar sensitivity to the given substance. It allows for comparative analysis of the differences in emissions between product alternatives (UDO DE HAES, 1996; WHITE et al., 1995).

The "less is better" methods may result in a poor accordance between the expected actual impact and the impact predicted by LCIA. Examples are given in Box 1. Most "less is better" methods are, among others, strongly debated for their inability to discriminate between processes with emissions causing concentrations below and above a threshold value (first and second example in Box 1). The most radical suggestions for an improved impact assessment is put forward by WHITE et al. (1995), and follows the principle of "only above threshold":

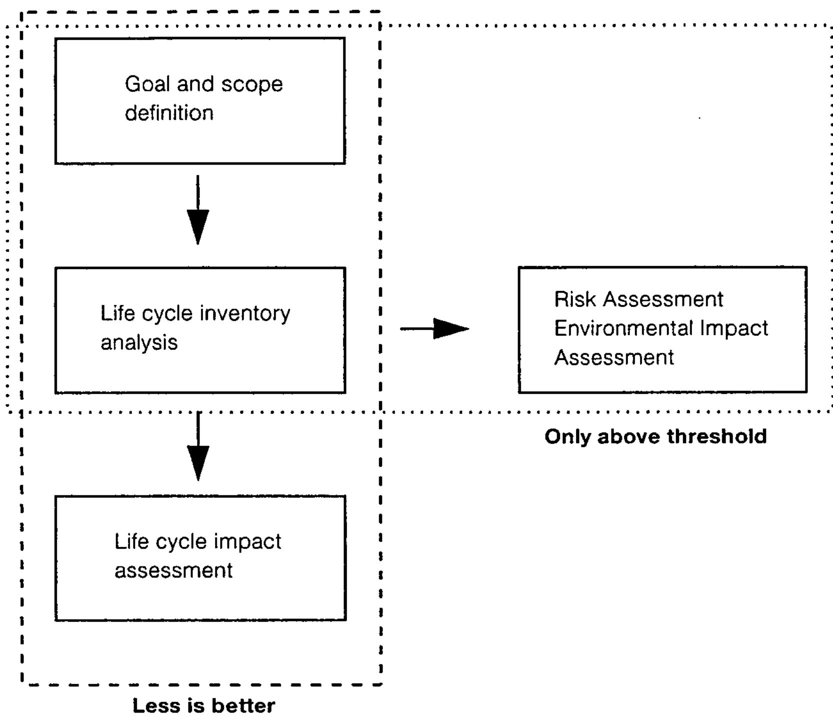

Fig. 1: The frameworks as usually drawn for "less is better" and "only above threshold" methods, and the relation between them (WHITE et al., 1995)

In "only above threshold" methods, those processes are identified that have the largest share of emissions in the product's life cycle. For these processes, additional information is gathered about the actual location. This site-information is next used to predict surpassing of threshold values, for instance with help of analytical tools as used in risk assessment and environmental impact assessment. These methods provide a higher accuracy of predicting human toxicity impact for the selected processes, under the restriction that only emissions are taken into account that occur at sites where thresholds are surpassed (UDO DE HAES, 1996; WHITE et al., 1995).

Figure 1 presents the frameworks usually drawn for "less is better" and "only above threshold" methods, and the relation between these frameworks. The two principles are often put forward as fundamentally different and incompatible with each other, because "less is better" methods are associated with (dis)advantages that should manifest themselves opposed to (dis)advantages of the "only above threshold methods" (→ *Fig. 2*). Major advantages of "only above threshold" methods are considered to be their accuracy in predicting actual impact, because of their ability to take temporal and spatial differentiation into account. Major advantages of "less is better" methods are seen in their limited requirement of additional data, which makes these methods simple to use and allows assessment of processes that are taking place in the future or are insufficiently specified in time, place or otherwise. (BARNTHOUSE et al., 1997; UDO DE HAES, 1996; WHITE et al., 1995) As we will show in the next sections, we only partly agree on this evaluation of "less is better" and "only above threshold" methods.

	Less is better	Only above threshold
Accordance between predicted and actual impact	–	+
Ability for temporal and spatial differentiation	–	+
Limited requirement of data	+	–
Ability to assess "non-defined" processes	+	–
Simplicity to use	+	–

Fig. 2: Advantages and disadvantages that are usually associated to manifest themselves opposite between "less is better" methods and "only above threshold" methods (WHITE et al., 1995). Non-defined processes are those taking place in the unknown future or those insufficiently specified in time, place or otherwise

3 No-Effect-Levels

The discussion about the principles of "less is better" and "only above threshold" is especially relevant with regard to human toxicity. Traditionally, human toxicity assessment has focused on quantifying the probability of surpassing thresholds (like no-effect-levels or regulatory standards) in the direct vicinity of an emission source. This focus is directly related to the perceived local character of environmental problems that society faced some decades ago: Increased pollution levels could in general be traced back to a neighbouring single source, and risky situations could be prevented by keeping the emissions from that single source under control. Environmental and human protection mainly focused on risk prevention from single sources. Risk was in this context interpreted as concentration levels above a given threshold. Since then, the environmental situation and our understanding of environmental risks has changed.

Effective regulation of the main individual sources in many industrialised countries has led to a situation in which risks from individual sources in local situations are prevented in most cases, and where total emissions from all large individual sources in general have been reduced substantially. At the same time, there has been a steady increase in product manufacture and consumption, leading to constantly growing flows of energy and materials throughout society, reflected in increased activities in all the processes required to maintain these flows. This has created an intricate and diffuse net of emission sources. In addition, it has become evident that substances with long residence times and high mobility may travel over fairly long distances before they arrive at the areas where they cause the impact. Receiving areas from single sources show overlap, and concentration levels at any point are often the result from many sources together rather than from a single source alone (POTTING and HAUSCHILD, 1997).

Many sources together may in some exceptional situations cause concentration levels above human toxicity thresholds (POTTING and HAUSCHILD, 1997), but also this will for the greater part be avoided as result of the effective implementation of control measures. However, whereas the existence of no-effect-levels was once taken for granted, there is nowadays growing evidence that substances also may have effect below those assumed no-effect-levels. The absence of a no-effect-level for many mutagenic substances is a well-known fact and follows from the effect mechanism of these substances (KLAASSEN et al., 1986). However, there is a growing body of large epidemiological studies showing small, yet definite increases in impact on humans associated with increases in air pollution like particulate matter and ozone (and plausibly also sulfur dioxide) (ExternE 1995).

The emergence of an intricate and diffuse net of weak sources has lead to a widespread presence of a number of different substances. While exposure to individual substances may remain below the (debated) no-effect-level, the impact of exposures to a combination of different substances with similar effect mechanisms and thus contributing to the same toxic effect, can be additive or even synergistic. This notion is supported by a number of observations of effects on human beings and animals which are highly suspected to relate to such combined exposures. Examples of such observations are the reduced sperm quality in men, the increase in testicle cancer, the relative increase in female trouts in some water bodies (TOPPARI et al., 1995) and the increase in asthma and allergy among humans in Western European countries.

The use of no-effect-levels has thus shown to be not so well-founded, while at the same time the impact of human exposures to a mixture of substances is unknown, and such exposures have become important due to the intricate and diffuse net of sources. It has therefore become relevant to prevent pollution levels below and above no-effect-levels, since less pollution is less impact and "less impact is better".

Exposure situations below thresholds can no longer be disregarded in a strategy of general prevention of impact, though an "only above threshold" approach may have preference when one aims for instance to evaluate compliance of processes with regulatory standards concerning the local environment.

4 Data Availability

LCA focuses on the entire life cycle of a product: from the extraction and processing of raw materials, through the manufacture, distribution and use of the product, to the final processing of the disposed product. Each stage may consist of a number of processes which each includes one or more inputs and outputs. Each input can be followed upstream to its origin and each output downstream to its final end. The total of connected processes is called a product system.

It is easy to see that a product system becomes rather complex as a product consists of more than one material or component. But even one material or component may represent a complex subsystem: A material like polyamide can be synthesized by many, very different technologies, and each technology can be applied by several producers. These production sites may in principle be located all over the world, and often it is not known which production site is the actual one for the analysed product system. Furthermore, the processes in one product system normally relate to different points in time. The widely distributed and often unknown location of production sites, plus the involvement of processes taking place in future (and the past), can make data collection difficult. That is the reason why LCA is often forced to use data that represents an average over different sites, or data that are estimates for processes taking place in the unknown future (or past).

The multiplicity of processes and technologies can make the collection of inventory data a very time-consuming activity. The effort to limit the amount of data per process in Life

Cycle Inventory (LCI) is given as one reason to avoid site-considerations in LCIA (HEIJUNGS et al., 1992). The use of data representing an average over sites, or data functioning as estimate for an unknown future (or past), can make it more difficult to apply site-specific LCIA. Some applications do also not need or explicitly want to avoid site-considerations influencing the results of LCA, e.g. ecolabeling may for political reasons wish to avoid favouring of certain regions at the expense of others. For this application, site-considerations in LCIA should not influence the results.

Data availability is not always a problem. Some spatial data, like the geographical location of the emission or roughly the height of release, are often already given by or logically follows from inventory analysis. In some applications, access to an abundance of temporal and spatial detail about main processes may even be expected. Companies performing their own LCA for product development for example, are expected to have access to all necessary information about their own processes, and they have strong arguments to require such information from their main suppliers. For these processes, it might thus be possible to apply an impact assessment with quite some spatial and temporal detail.

Availability and additional requirements of data play a decisive role in the choice of LCIA methods and therewith the level of detail in human exposure assessment, but as the next section will show, not in the choice to follow either a "less is better" or "only above threshold" principle.

5 Existing Modelling of Human Toxicity in LCA

First generation LCIA methods calculated so called critical volumes by dividing an emission by a given threshold value (HABERSATTER, 1991). These methods have often been criticized for the lack of fate considerations. Second generation LCIA methods therefore include considerations about the intrinsic ability of substances to disperse in the environment:

GUINÉE et al. (1996) and JOLLIET (1996) both use full fate modelling to establish an equivalency factor for each substance. The modelling from JOLLIET (1996) is based on empirical data and calculates concentration increases per unit of substance. GUINÉE et al. (1996) use steady-state multimedia modelling (Mackay type) to first calculate concentration increases per unit of substance, and next exposure increases through inhalation (of air) and through ingestion (of food and water). A steady-state model quantifies the (bio)-degradation, (bio)accumulation and the trans-partitioning between the environmental media (air, water, soil, food chain) of a substance on the basis of a continuous inflow of this substance. Once equivalence factors have been calculated (only done once), their application in LCA is simple. However, the modelling to derive these factors needs a large input of data about the physical, chemical and biological characteristics of the substance, or is based on structure-activity relationships derived mainly from the lipophilicity of the substance (P_{ow}).

The possibility of establishing the human toxicity impact per unit of substance with full fate modelling is limited by the large uncertainties, limited availability of data about characteristics of many substances, and lack of appropriate models for generic fate-modelling (TUKKER, 1997; COWAN et al., 1995). That is an important reason why several second generation LCIA methods focus on partial fate modelling as being less data intensive and more transparent (HAUSCHILD and WENZEL, 1997; LINDFORS et al., 1995; WENZEL et al., 1997). The partial fate modelling from WENZEL et al. (1997) is restricted to main fate indicators like the final partitioning between environmental compartments, the bioconcentration and persistency properties of the substance, and a quantification of the human intakes and absorption efficiencies of the relevant media.

Full-fate as well as partial-fate methods have the advantage that this application does not require additional data from a typical LCI and therefore makes them applicable for non-defined processes in LCA. They have their starting point in a so called unit world, which means that all emissions disperse in the same environment, and arrive at sites that have the same sensitivity to the given substance. These methods made a great step towards a "less impact is better" principle by taking into account the intrinsic fate and effect potential of substances. On the other hand, they are poor at integrating spatial and temporal differentiation and therefore do not allow for threshold evaluation (→ *Fig. 3*).

The ExternE project (1995) has specifically focused on human impacts from concentration increases below and above thresholds, resulting from emissions of energy technologies. These concentration increases are established with high spatial resolution by atmospheric transport models of the Lagrangian and Gaussian type, and with a high spatial resolution related to the number of people actually exposed. The modelling requires detailed information about the location and source characteristics of these technologies, as well as about population densities of the receiving areas. Though exposures from energy production remain in general below no-effect-levels (→ *Box 1*), this method would in principle allow for threshold evaluation with a high degree of accuracy. However, the necessity of all this data additional to a typical LCI makes the approach of ExternE (1995) yet not easily feasible in LCIA (→ *Fig. 3*).

"Only above threshold" methods are generally known for combining application of analytical tools from Environmental Impact Assessment or Risk Assessment with data gathering additional to a typical LCI (see also Section 2 and Fig. 1). These tools predict environmental concentrations with an accuracy higher than the "less is better" methods discussed above, and therefore better allow for threshold evaluation. This is implemented by discarding any impact for exposure situations below threshold, and giving full emphasis to exposure situations above threshold. Extensive requirement of data additional to a typical LCI makes these tools not very feasible in a typical LCA (→ *Fig. 3*).

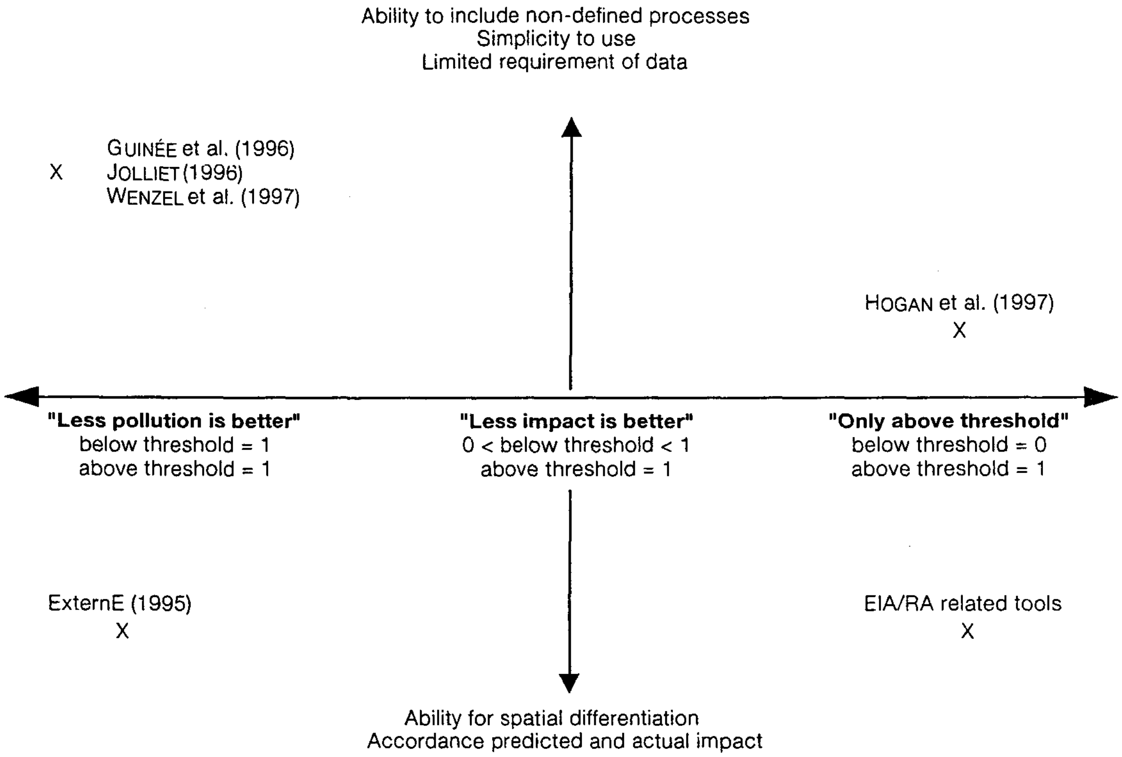

Fig. 3: Classification of existing methods for human toxicity assessment in LCA to the "less is better" or "only above threshold" principle, as well as positioning of each method towards the several (dis)advantages. Non-defined processes are those taking place in the unknown future, or insufficiently specified in time, place or otherwise. Developments are taking place to integrate some site-considerations in the methods of GUINÉE et al. (1996), JOLLIET (1996) and WENZEL et al. (1997), while RABL et al. (1998) are working on a method based on ExternE (1995) that requires less data to be applied in LCA

HOGAN et al. (1996) developed a method which is feasible in LCA and allows for threshold evaluation. Though this method provides less accuracy than the previous ones, it only needs the geographical locations of emissions as additional information (→ *Fig. 3*): Geographical locations of emissions are mapped with databases containing geographical information about air quality. HOGAN et al. (1996) only take into account emissions of priority substances, taking place in areas where human toxicity threshold values are already exceeded according to the US EPA's national air quality databases. The result is an adjusted inventory table that excludes emissions of non-priority substances as well as emission of priority substances in areas where no thresholds are exceeded (the impact is here set to zero). The remaining emissions are cumulated per substance and without further processing attributed to relevant toxicity sub-categories. HOGAN et al. (1996) do not perform a subsequent impact assessment (effect, fate and/or exposure modelling). This might be considered as a disadvantage.

6 Integration of Principles and Methods

There are three main routes of human exposure to environmental pollutants: (1) inhalation of air, (2) ingestion of food and water (and sometimes soil), and (3) penetration of the skin after contact with polluted surfaces (or sometimes with soil, water or air). The exposure of humans to environmental pollutants usually takes place via more than one route at the same time (multi-route exposure). LCA focuses usually on inhalation and ingestion only (though skin exposure might be of major relevance for some products like cloths or cosmetics).

Exposure to a particular substance is often (but not always) dominated by one of the main exposure routes. Among those, inhalatory exposures have a unique feature because they are ubiquitous and can thus not be avoided once a substance is present in air (WILLIAMS et al., s.d.). In addition, inhalatory exposures are often directly resulting from emissions to air in which dispersion and dilution (and often also removal) are fast processes.

Databases with geographical information about air quality as used by HOGAN et al. (1996) in a simple and feasible way permit for discrimination between situations with background exposures below and above thresholds. However, in many applications it is unsatisfactory to set the human toxicity impact to zero for exposure situations below threshold as HOGAN et al. (1996) do, and also the absence of a subsequent impact assessment can be considered as a disadvantage. Two solutions as already presaged by OLSEN (1997)

are possible: 1) a sub-category for exposure situation above threshold and a sub-category for exposure situation below threshold, 2) multiplying both sub-categories with their own factor expressing their relative importance (for example: below threshold = 0 < factor < 1, above threshold = 1). Both solutions can be combined with human toxicity assessment according to either GUINÉE et al. (1996), JOLLIET (1996) or WENZEL et al. (1997) to account for the intrinsic fate and effect potential from substances.

Combination of methods from HOGAN et al. (1996) with either GUINÉE et al. (1996), JOLLIET (1996) or WENZEL et al. (1997) are a major step in improving the accordance between the human toxicity impact predicted in LCIA, and the expected occurrence of the actual human toxicity impact. However, it does not yet solve the identified problems sufficiently. Though developments definitely are taking place, none of the methods for human toxicity assessment from either GUINÉE et al. (1996), JOLLIET (1996) or WENZEL et al. (1997) are able to deal satisfactorily with spatial differences related to source characteristics:

Dispersion and dilution of air emissions are, among other factors, very much influenced by source characteristics like release height and dynamics of the emission. The examples in Box 1 illustrate that the magnitude of exposure is not at all associated with the emitted amount if the source characteristics are not taken into account. In addition, the presence of a substance in the environment does not necessarily lead to exposure if no human beings are there. Population density and duration are important determinants of the magnitude of exposure.

In addition, the effective implementation of control measures in industrialised countries has led to a situation in which single sources as well as many sources together in most cases do not result in surpassing of – now debated – thresholds for human toxicity. However, there are still some exceptional situations (Example 1 and 2 in Box 1) where sources do evoke concentration levels above human toxicity thresholds (POTTING and HAUSCHILD 1997).

The combined methods from HOGAN et al. (1996) with either GUINÉE et al. (1996), JOLLIET (1996) or WENZEL et al. (1997) can be extended with factors allowing spatial differentiation into source type related concentration increases and exposure situations. Section 7 presents a framework to derive such factors, and to combine them with the above-mentioned methods.

7 Human Toxicity from Air Emissions in LCA

Based on considerations presented in Section 6, a framework can be drawn to derive factors that account for the main spatial determinants in human toxicity assessment in LCA from air emission. The available methods and/or data are given for each step:

Identification of source types and classification of processes
Typical "less is better" methods do not yet differentiate between source characteristics. This leads to an overestimation of the importance of high stack emissions over low stack emissions (see Example 3 in Box 1), and to an underestimation of the importance of indoor emissions compared to low stack emissions (see Example 1 in Box 1). It seems useful to discriminate between the following source types: high/low stacks, high/low mobile exhaust, and indoor situations. It is expected that the different types of industrial processes can be attributed to one of these five source categories. The Dutch Emission Registration contains a database with detailed information about the physical conditions and circumstances of the largest part of Dutch industry (DRAAIJERS et al., 1997). This data base may be used to identify the relevant types of industrial processes that can be attributed to each source category.

Area of concentration increase
In general, there is only a short time (a few hours) and distance (a few hundred metres) between the occurrence of an outdoor emission and the increase and decrease of concentration of the emitted compound in ambient air. The relation between source height and the area of concentration increase can be calculated with atmospheric transport models of the Gaussian or Lagrangian type. The area of emission distribution per source type can roughly be calculated on the basis of typical characteristics of that source type, and on the basis of annual and average atmospheric conditions.

Environmental concentration above or below thresholds
Environmental concentrations are the result of the already existing background concentration together with the concentration increase due to the considered emission. Most sources are regulated in such way that concentrations above threshold are avoided. As a default situation, therefore, the sum of background concentration and concentration increase can be taken as relatively low (below threshold). Databases about prevailing environmental concentrations like the one used by HOGAN et al. (1996) may give information about areas where concentrations are already exceeded. Typical exceptions where sources in itself, or together with others are able to surpass thresholds on a local scale (like heavy urban traffic or indoors) can be identified on the basis of literature. Exposure situations above threshold can be given a separate impact subcategory, or can be aggregated with exposure situations below threshold by multiplying each subcategory with its own factor expressing the relative importance (for example: below threshold = 0 < factor < 1, above threshold = 1).

Population densities
Per source type, the number of people exposed will vary because of the different areas of concentration increase. However, the number of those exposed can also vary largely within one source type since population densities will be different from location to location. It has to be validated whether the distinction of a small number of typical popula-

tion densities offers sufficient resolving power for use in LCA. Typical population densities may be: densely populated (urban and built-up areas), sparsely populated (rural) and indoor situations.

Resulting impact assessment model
With the above information, human toxicity from air emission can be calculated very simply:

$$\text{Human toxicity(air)} = E_{air} \times FI_{source\ type} \times TI_{location} \times EI_{location}$$
$$(1 \times 5 \times 3 \times 2 = 30)$$

Where:

E_{air}	=	Emission to air (in gram)
$FI_{source\ type}$	=	Fate information (in m^2) connecting the selected source type (high/ low point sources, high/low mobile sources, indoors) to a default area of concentration increase
$TI_{location}$	=	Target information (in number of persons) connecting the location of emission to the selected population density (density, sparsely, indoor) with a default number of exposed persons
$EI_{location}$	=	Effect information connecting the emission location to exposure situation above or below threshold (for example: below threshold = 0 < factor < 1, above threshold = 1)

The application of this model in LCA leads to 30 different combinations. This seems more complicated, however, than it will be in reality since some combinations are not very obvious. For example, the indoor population density is only relevant for indoor emissions, and this alone leads to a reduction of 18 combinations. The only data needed in addition to a typical LCI is the source type from which the emission originates, and the geographical location where the emission take place. In general, the source type result from the originating process. The geographical location of production processes is often already roughly known, since it is needed to calculate the interventions from transport.

8 Conclusions

Two main positions dominate the ongoing discussion about possibilities and limitation of LCIA to predict actual impact: the still typical "less is better" methods, and the later introduced "only above threshold" methods. As shown in this article and in contrast with the common opinion, they are not incompatible and the only fundamental difference between both types of methods is how they deal with threshold values:

"Only above threshold" methods disregard exposures below threshold (below threshold = 0, above threshold = 1), while "less is better" methods take into account both exposures below and above threshold (though exposures above may be given more importance than exposure below threshold: below threshold = 0 < factor 1, above threshold = 1).

Availability and additional requirements of data play a decisive role in the choice of LCIA methods and therewith the possible level of detail in human exposure assessment, but not in the choice to follow either a "less is better" or "only above threshold" method. Both types of methods can make use, and factually do make use of a collection of similar analytical tools which range from no additional data requirements to extensive additional data requirements.

The choice for either a "less is better" or an "only above threshold" approach may to some extent relate to a value-based preference (Barnthouse et al., 1997), however, a major incentive is provided by the regulatory field of environmental and human protection that is supported by each approach:

- "Only above threshold" methods support the more traditional concept of risk prevention by keeping concentration levels in the direct vicinity of individual sources below human toxicity threshold values.
- "Less is better" methods focus on general prevention of concentration levels that result from multiple sources, often far away, and may consist of a mixture of substances that can have additive or even synergistic effects (though each individual may remain below threshold values).

Both regulatory fields are supplementary (rather than exclusive). They express a shift in attention from the traditional environmental problems (still relevant, but largely under control now) to the present much more complex environmental situation.

A main challenge is to develop a "less impact is better" method, which, with limited need of additional data, improves the accordance between the impact predicted by LCIA, and the expected occurrence of actual impact. We propose a framework to derive an improved model for the assessment of human toxicity from air emissions, consisting of four steps:

1. Identification of source types (like high/low point sources, mobile sources and indoor sources), and classification of processes to these sources types on the basis empirical data about process characteristics

For each source type

2. Estimation of the area with increased concentration by atmospheric transport models (Lagrangian and Gaussian type)

3. Estimation of exposure situation above or below thresholds on the basis of typical background concentrations

4. Estimation of amount of exposed people on the basis of typical population densities (urban/rural, indoors)

The model derived from this framework is expected to combine the benefits of typical "less is better" methods with

those from an "only above threshold" method as from HOGAN et al. (1996). Elaboration of the framework is underway in a Danish method development program sponsored by the Danish Agency for Industry and Trade (through the EUREKA project LCAGAPS), the Danish Environmental Protection Agency and a training and mobility grant from the EU commission.

9 References

BARNTHOUSE, L., J. FAVA, K. HUMPRHEYS, R. HUNT, L. LAIBSON, S. NOESEN, J. OWENS, J. TODD, B. VIGON, K. WEITZ and J. YOUNG (1997): Life-cycle impact assessment. State-of-the-art. United States of America, Pensacola, SETAC-USA

CONSOLI, F., D. ALLEN, I. BOUSTEAD, J. FAVA, W. FRANKLIN, A.A. JENSEN, N. DE OUDE, R. PARRISH, D. POSTLETHWAITE, B. QUAY, J. SIÉGUIN and B. VIGON (Eds.) (1993): Guidelines for life-cycle assessment. A code of practice. Belgium, Brussels, SETAC-Europe and SETAC-USA

COWAN, C.E., D. MACKAY, T.C.J. FEIJTEL, D. VAN DE MEENT, A. DI GUARDO J. DAVIES and N. MACKAY (Eds.) (1995): The multimedia fate model: A vital tool for predicting the fate of chemicals. SETAC PRESS, Pensacola, Florida

DRAAIJERS, G.P.J., J.J.M. BERDOWSKI, H. LENEMAN, G.A. ROOD, D.J. DE VRIES and E.A. ZONNEVELD (1994): Emission in The Netherlands, trends, themes and target groups . 1995 and estimates of 1996 (in Dutch). The Netherlands, The Hague, ministry of Housing, Spatial Planning and the Environment (VROM)

FAVA, J., F. CONSOLI, R. DENISON, K. DICKSON, T. MOHIN and B. VIGON (eds.) (1993): A conceptual framework for life-cycle impact assessment. Belgium, Brussels, SETAC-Europe and SETAC-USA

ExternE (1995): Externalities of energy. Volume 2: Methodology. EUR 16521 EN. Luxembourg, European Community

GUINÉE, J., R. HEIJUNGS, L. VAN OERS, D. VAN DE MEENT, T. VERMEIRE, M. RIKKEN (1996): LCA impact assessment of toxic releases. Generic modelling of fate, exposure and effect for ecosystems and human beings with data for 100 chemicals. The Netherlands, Leiden, Centre of Environmental Science of Leiden University

GUSTAFSSON, H. (1992): Building materials identified as major sources for indoor air pollutants. A critical review of case studies. Document D10: 1992. Sweden, Boras, Swedish council for building research

HABERSATTER, K. (1991): Oekobilanz von Packstoffen. Stand 1990. Switzerland, Bern, BUWAL

HAUSCHILD, M. and WENZEL, H. (1997): Environmental assessment of industrial products. Vol. 2: Scientific background. Chapman and Hall, United Kingdom

HEIJUNGS, R., J. GUINÉE, G. HUPPES, R.M. LANKREIJER, H.A. UDO DE HAES, A. WEGENER SLEESWIJK, A.M.M. ANSEMS, P.G. EGGELS, R. VAN DUIN and H.P. DE GOEDE (1992): Environmental life cycle assessment of products. Guide and background, The Netherlands, Leiden, Centre of Environmental Science of Leiden University

HOGAN, L.M., R.T. BEAL and G. HUNT (1996): Threshold inventory interpretation methodology. A case study of three juice container systems. Int. J. LCA, vol. 1, issue 3, p. 159-167

ISO/TC207/SC5N77 (1996): Environmental management – life cycle assessment – principles and framework. Reconstructed draft 14040. Le comité membre français AFNOR of ISO

JOLLIET, O. and P. CRETTAZ (1996): Calculation of fate and exposure coefficients for life cycle toxicity assessment; second draft. Switzerland, Lausanne, Institute of Soil and Water Management from the Swiss Federal Institute of Technology

KILDE, N. (1995): Energy consumption and emissions in transport of products in 1990 (in Danish). Denmark, Roskilde, Forskningscenter Risø

KLAASSEN, C.D., M.O. AMDUR and J.DOULL (1986): Casarett and Doull's toxicology. The basic science of poisons. Third edition. New York, Macmillam Publishing Company

LINDFORS, L.-G., K. CHRISTIANSEN, L. HOFFMAN, Y. VIRTANEN, V. JUNTILLA, O.-J. HANSSEN, A. RØNNING, T. EKVAL and G. FINNVEDEN (1995): Nordic Guidelines on life-cycle assessment. Nord 1995; 20. Denmark, Copenhagen, Nordic Council of Ministers

OLSEN, S.I. (1997): Life-cycle assessment of basic chemicals. PhD-thesis. Denmark, Lyngby, Institute of Manufacturing Engineering

POTTING J. and K. BLOK (1994): Spatial aspects of life-cycle impact assessment. In: Integrating impact assessment into LCA. Proceedings of the LCA symposium held at the fourth SETAC-Europe Congress, 11-14 April 1994 at the Free University of Brussels in Belgium. Belgium, Brussels, SETAC-Europe

POTTING, J. and M. HAUSCHILD (1997): Predicted Environmental impact and expected occurrence of actual environmental impact. Part 1: The linear nature of environmental impact from emissions in life-cycle assessment. Int. J. LCA, Vol. 2, Issue 3, p. 171-177

RABL, A. and J.V. SPADARO (1998): Estimates of real damage from air pollution: Site dependency and simple impact indices for LCA. Contribution to the 8th annual meeting of SETAC-Europe, 14-18 April 1998 in Bourdeaux, France. France, Paris, Ecole de Mines de Paris

TOPPARI, J., J.C. LARSEN, P. CHRISTIANSEN, A. GIWERCMAN, P. GRANDJEAN, L.J. GUILLETTE, B. JÉGOU, T.K. JENSEN, P. JOUANNET, N. KEIDING, H. LEFFERS, J.A. MCLACHLAN, O. MEYER, J. MÜLLER, E. RAJPERT-DEMEYTS, T. SCHEIKE, R. SHAPRE, J. SUMPTER and N.E. SKAKKEBÆK (1995): Male reproductive health and environmental chemicals with estrogenic effects. Miljøprojekt nr. 290. Denmark, Copenhagen, Danish EPA

TUKKER, A. (1997): Combining SFA and LCA: The Swedish PVC Analysis. Proceedings of the fifth LCA case studies symposium, 2 December in Brussels. Belgium, Brussels, SETAC-Europe

UDO DE HAES, H.A. (ed.) (1996): Towards a methodology for life-cycle impact assessment. Belgium, Brussels, SETAC-Europe

WENZEL, H., M. HAUSCHILD and L. ALTING (1997): Environmental assessment of industrial products. Vol. 1: Methodology, tools and case studies in product development. Chapman and Hall, United Kingdom

WHITE, P., B. DE SMET, H.A. UDO DE HAES, R. HEIJUNGS (1995): LCA back on track, but is it one track or two? LCA news from SETAC-Europe, vol. 5, issue 3, p. 2-5

WILLIAMS, M. (Ed.) (s.d.): Exposure assessment. Report number 1. Cost 613/2 Report series on air pollution epidemiology. Directorate-General XII for Science, Research and Development from the Commission of the European Communities